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Technical Report No. 2

SEISMIC AFTERSHOCK INVESTIGATIONS--PROJECT VELA UNIFORM
RECORDING OF MICRO-EARTHQUAKES NEAR SOCORRO,
NEW MEXICO, DECEMBER 24-27, 1961

Prepared for:

Air Force Technical Applications Center
Washington 25, D. C.

Under Contract No. AF 49(638)-1025

By: A. L. Lange

SRI Project No. PHU-4322

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PREFACE

The Socorro project was carried out with the cooperation and generous assistance of members of the New Mexico Institute of Mining and Technology. We thank in particular E. J. Workman, president, and A. R. Sanford, assistant professor, for extending the invitation, and Francis Hall for serving as geologic guide and helping in choosing sites, gaining entry, and arranging for equipment.

The field work and interpretations were carried out under the sponsorship of Stanford Research Institute (SRI) with equipment made available to SRI by the Air Force Office of Scientific Research under Project VELA of the Advanced Research Projects Agency. Under Contract No. AF 49(637)-1205 with the Air Force Technical Applications Center, SRI is studying the aftershock activity of earthquakes and underground nuclear explosions and its implications in on-site inspection of clandestine nuclear tests. Because of the pertinence of the Socorro study to this project, this report is submitted under the current contract.

W. H. Westphal directed the research; the field work was performed by Mr. Westphal, G. S. Brink, Dan McLachlan, Jr., and A. L. Lange. L. C. Harlen prepared playback records. Data interpretation and report preparation were done by A. L. Lange.

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INTRODUCTION

Project VELA is an extensive research program being conducted by the Advanced Research Projects Agency with the objective of developing effective and reliable techniques that may be useful in monitoring an international agreement to ban the testing of nuclear weapons. One proposed method of identifying a seismic event as an earthquake or a clandestine underground explosion is the monitoring of post-event seismic noises (aftershocks) produced by the primary event. The basic premise of post-event seismic monitoring is that aftershocks from earthquakes and underground explosions have different characteristics. As part of Project VELA, Stanford Research Institute (SRI) has undertaken a program of monitoring post-event seismic disturbances following both earthquakes and underground nuclear explosions to determine the validity of this premise. The specific objectives are

(1) to determine the characteristics of earthquake- and explosion-induced aftershock sequences

(2) to study the relationship of the foci of earthquake aftershocks to the focus of the primary earthquake

(3) to improve methods of data analysis and interpretation of the results of aftershock monitoring.

The volcanic region of Socorro Mountain in Socorro County, New Mexico, is a center of micro-earthquake activity; hence, it is of interest to the SRI aftershock recording program. The area was favorable for investigation because seismic studies were already under way there by the New Mexico Institute of Mining and Technology (NMIMT)[1*] and because it was convenient to Carlsbad, New Mexico, where the equipment was used to monitor aftershock activity of the Gnome explosion on December 10, 1961. Thus, in the hope of gathering general data on seismicity in a new area, SRI arranged to record the micro-earthquakes in the region from December 24 through 27, 1961. This is a report on the seismic activity recorded during the four day interval.

*Numbered references are listed at the end of this report.

OPERATIONS

Three recording seismographs returning from use at the Gnome test on December 10, 1961, were set up at the following locations (See Fig. 1):

Station	Location
A (Windmill)	sec. 23, T. 3 S., R. 2W.; 34°02'18" N, 107°01'13" W
B (Chupadero)	sec. 5, T. 4 S., R. 1W.; 33°59'38" N, 106°58'24" W
C (Blue Canyon)	sec. 16, T. 3 S., R. 1W.; 34°02'36" N, 106°57'15" W

The sites were located to form a triangle surrounding the center of seismic activity in the area as determined by NMIMT studies. Each station contained an array of six vertical seismometers whose outputs were recorded continuously on magnetic tape with WWV time signals. The layouts of the seismometer arrays are shown in Fig. 2.

The stations recorded from 2000 GCT, December 24, to 0310 GCT, December 28.

GEOLOGY AND SEISMICITY OF THE SOCORRO AREA

General Geology

The Socorro and Chupadero Mountains, in which the seismograph stations were located, are part of a north-south trending chain of mountains near the west boundary of the Mexican Highland section of the Basin and Range physiographic province. This region is characterized by isolated ranges of block-faulted mountains arranged in the en echelon fashion typical of Nevada's Great Basin, and surrounded by alluvial plains. The highest peak in the Socorro Range is Socorro Peak, 2.2 km in elevation, more than 900 meters higher than the aggraded valley of the Rio Grande, 6.5 km to the east, in which the town of Socorro was founded. The Socorro Range is separated from the similar Lemitar Range to the north by Nogal Canyon, which drains the flat plain of Snake Ranch Valley lying west of the range. The Range is bounded on the south by Socorro Canyon which contains "... a deposit of fuller's earth overlain by basalt."[2] The Chupadero Mountains

FIG. 1 LOCATION OF SEISMOGRAPHS AT SOCORRO PEAK

RA-4382-10

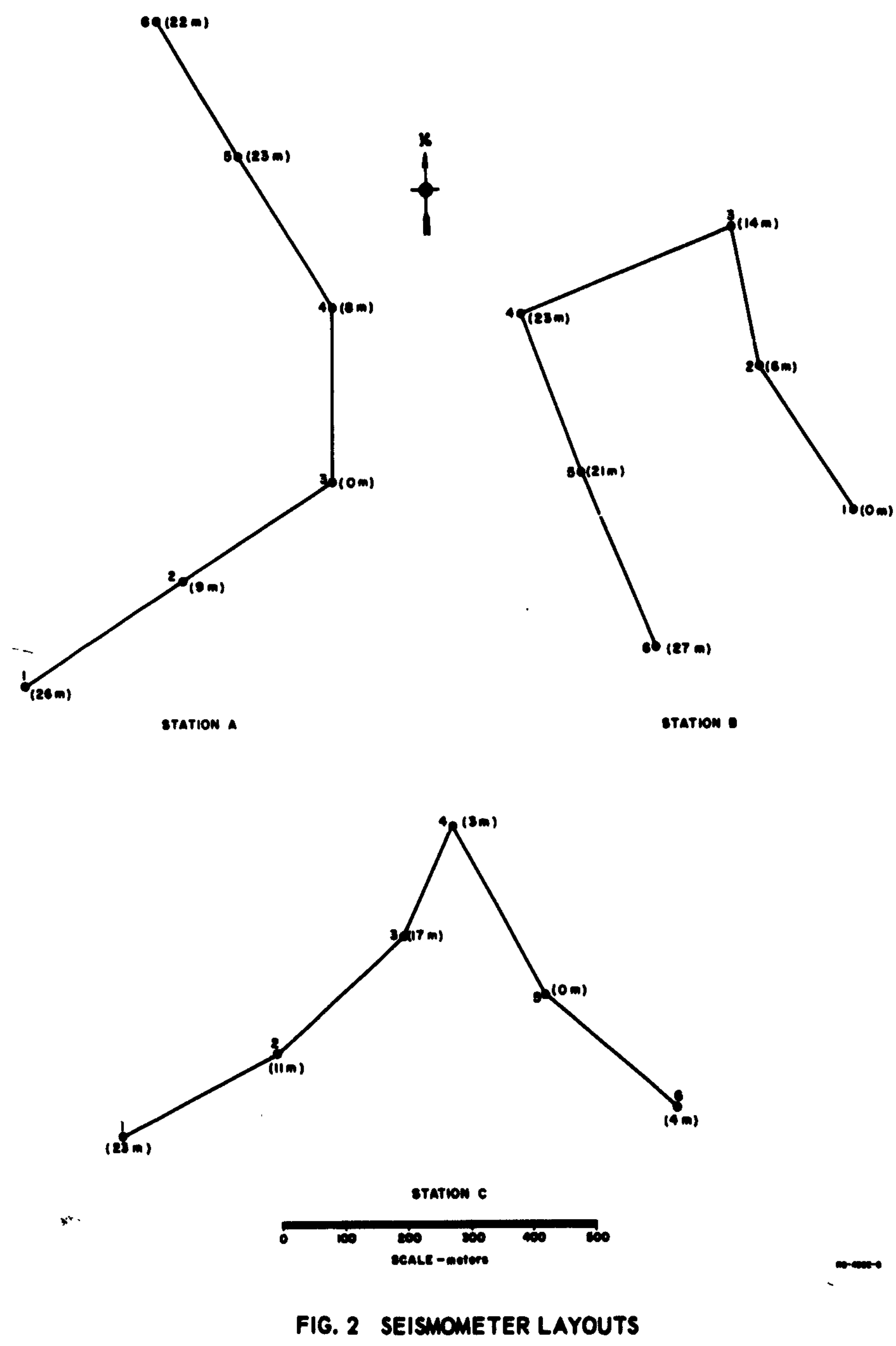

FIG. 2 SEISMOMETER LAYOUTS

are a continuation of the chain south of Socorro Canyon, but their relief is more subdued; their highest elevation is about 1.9 km.

Structurally the Socorro Range is a system of westward-dipping Tertiary igneous rocks extruded upon Paleozoic limestone and a Pre-Cambrian base. Its structure differs from that typical of the area in that it is anticlinal, according to Darton,[2] who finds no evidence of block faulting. Local faulting, however, has broken up the strata and permitted venting during volcanic eruptions; to the north of Blue Canyon in the Socorro Range the complex fault pattern has been extensively mineralized.

The Chupadero Mountains are composed of eastward-dipping volcanic rocks; the presumed underlying Paleozoic and Pre-Cambrian rocks are not exposed. Miesch regards the Chupaderos to be a horst or elevated block "...uplifted between relatively depressed areas now covered by fanglomerates."[4]

Geology of the Station Sites

Station A (Windmill) was set up at a well on the west side of the Socorro range, on a mesa of Tertiary and Quaternary lavas, overlain to the west by upper Miocene and lower Pliocene sediments of the Sante Fe formation. It is likely that the hard rock extends from the station sites through the main body of the Socorro range, though low-velocity Santa Fe clays may possible intervene. Seismometers were arranged in the form of an L (Fig. 2), approximately 300 meters apart, on bedrock. The maximum elevation differential among the phones was 26 meters.

Station B (Chupadero) was a U-shaped array set up approximately 1.5 km south of Highway 60 in the Chupadero Range (Fig. 2). The limbs of the configuration followed the edges of a shallow alluvial valley, so that all seismometers were either directly on volcanic breccia or on a negligibly-thin cover of alluvium. The surrounding geology is a complex assemblage of volcanic strata and intrusive dikes, which have been mapped by Miesch (Fig. 3). The array enclosed dikes of Quaternary basalt and

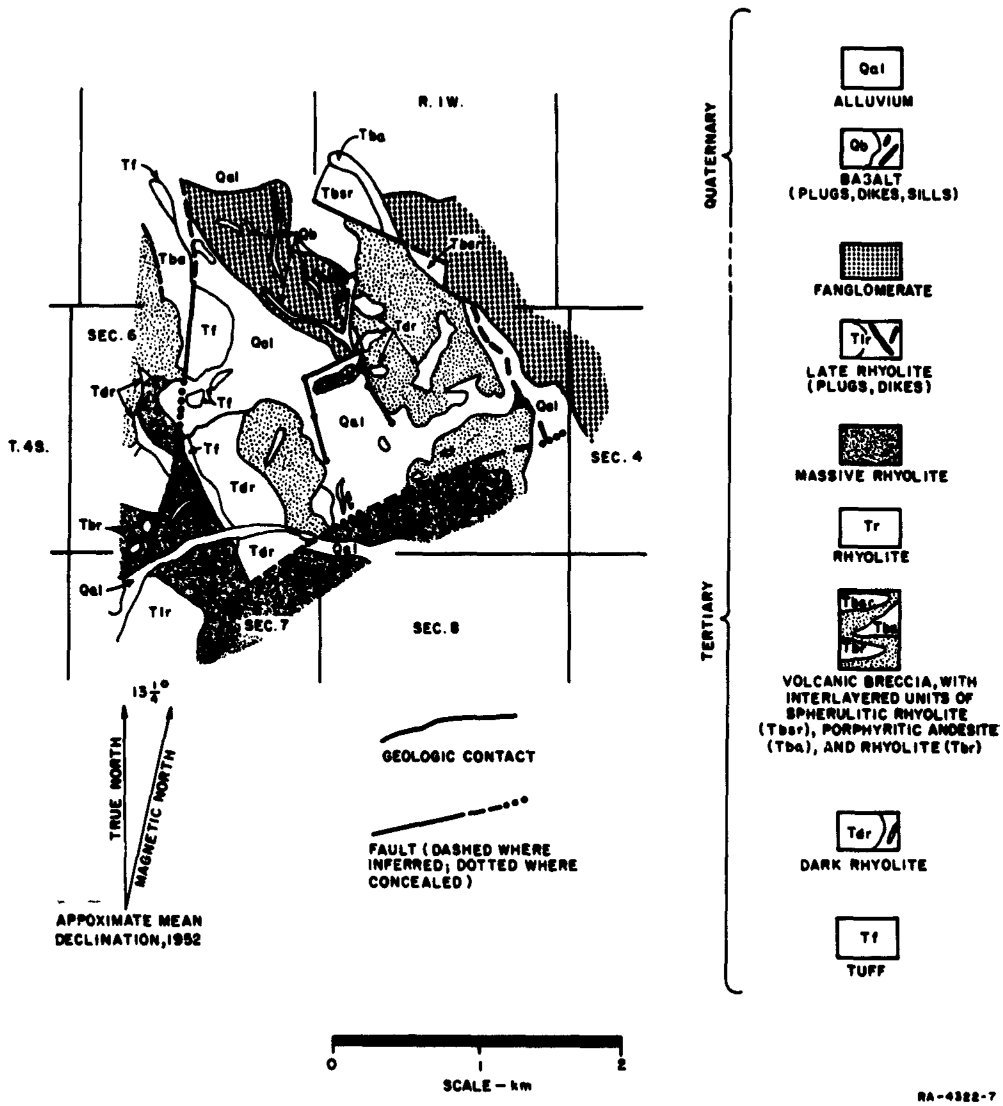

FIG. 3 GEOLOGY SURROUNDING STATION B (After Miesch[3])

Tertiary rhyolite. The entire station is surrounded by a triangular network of inferred or observed faults. Just north of Highway 60 and lying between Socorro Peak and Station B is a prominent mesa--Black Mountain--formed of clays capped by basalt; the clay beds are probably thick enough to appreciably influence seismic wave directions and velocities between Socorro Peak and Station B. There was a maximum altitude differential of 27 meters among the seismometers in the array.

Station C (Blue Canyon) was an L-shaped configuration (Fig. 2) established in Blue Canyon of the Socorro Range on the testing ground of NMIMT. The seismometers were emplaced on volcanic outcrops with a maximum of 23 meters of elevation differential among them. According to the state geologic map and Lasky's survey of the mining district just north of the site, the volcanics include Tertiary andesites, rhyolite, basalt, tuff, agglomerate, and ash, resting upon rocks of the Pennsylvanian Magdalena group (limestone, sandstone, and shale), which in turn overlie a basement of Pre-Cambrian granite, shist, and quartzite.[3] The canyon walls of thick unconsolidated ash beds interlayered with basalts indicate a likelihood of seismic anomalies across the array.

Seismicity

The extensive faulting and volcanism apparent in the rocks of the Socorro range are not to be relegated to past geologic history; activity at depth is evident today from the numerous micro-earthquakes observed on seismographs mounted in bedrock tunnels of Socorro Mountain by NMIMT. A recent report by Sanford and Holmes summarizes their findings. In 1961, 417 shocks having S-P intervals of less than 2.3 sec (local in orgin) were recorded; two of these were felt in Socorro with an intensity of IV. On the basis of data from a tripartite array of seismographs most of the foci were calculated to be in the Socorro range, particularly in the area of Blue Canyon and Black Mountain, at depths from 2.5 to 6.5 km. Sanford and Holmes point out that their assumptions of a simple velocity-with-depth distribution and straight-line travel paths might lead to errors because of faulting and tilting of different rock types that could result in more complex raypaths.

From analyses of seismic data from nearby explosions and distant earthquakes, Sanford and Holmes deduced a velocity distribution with depth, z, down to a depth 0.8 km beneath the surface of

$$v = 3.2 + 2.35\, z$$

as illustrated in Fig. 4. The raypath in this case is a circular arc. Below 0.8 km, the path is assumed to be a straight line. The formula prescribes a surface velocity of 3.2 km/sec, and a velocity of 5.2 km/sec below 0.8 km.

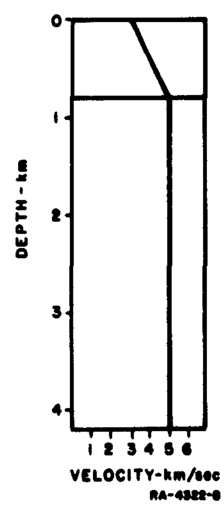

FIG. 4 ASSUMED VELOCITY DISTRIBUTION IN THE SOCORRO AREA

RESULTS

During the recording interval from 2000 GCT, December 24, to 0310 GCT, December 28, 1961, nine seismic events were observed at one or more stations as shown in Table I. The appendix gives data on the nine events.

Table I

SEISMIC EVENTS

Event No.	Date	First Arrival Time (GCT)	Observing Stations
1	12/25/61	16:51:55	C[a]
2	12/26/61	04:50:40	A,C
3	12/26/61	07:51:40.569	A,B,C
4	12/26/61	08:32:10	A,B,C
5	12/26/61	16:50:46	C
6	12/26/61	21:00:30	A,B
7	12/27/61	20:13:37.48	A,B,C
8	12/27/61	21:03:39.7	A,B,C
9	12/27/61	21:14:25	A,B

[a]Stations A and B were not recording at the time.

In four cases (Events 3, 4, 7, and 8) wave vectors could be determined. The results are summarized graphically in Figs. 5 through 8. For those events where S-P intervals were recognized, focal distances were calculated using Sanford and Holmes' P-wave velocity of 5.2 km/sec. Results are given in Table II.

Events 3 and 7 originated within about 25 km of Socorro, probably north or northeast of the town. Events 1, 2, 4, and 8 had S-P times of less than 2 sec, and hence originated somewhere in the Socorro Range within 15 km of the recording stations. Events 6 and 9 were distant earthquakes, approximately 200 km and 75 km, respectively. No approximate location could be assigned to Event 5.

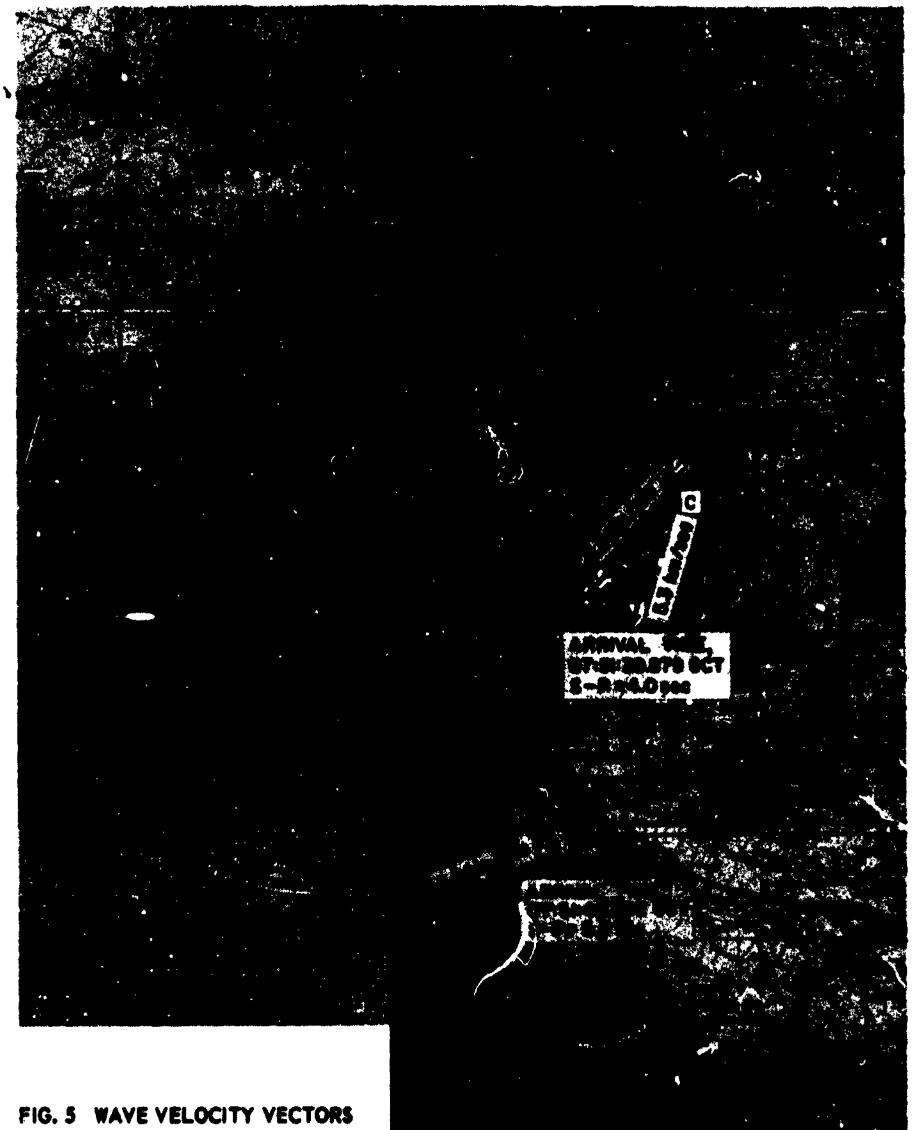

FIG. 5 WAVE VELOCITY VECTORS AND S-P TIMES OF EVENT 3

RA-4362-9

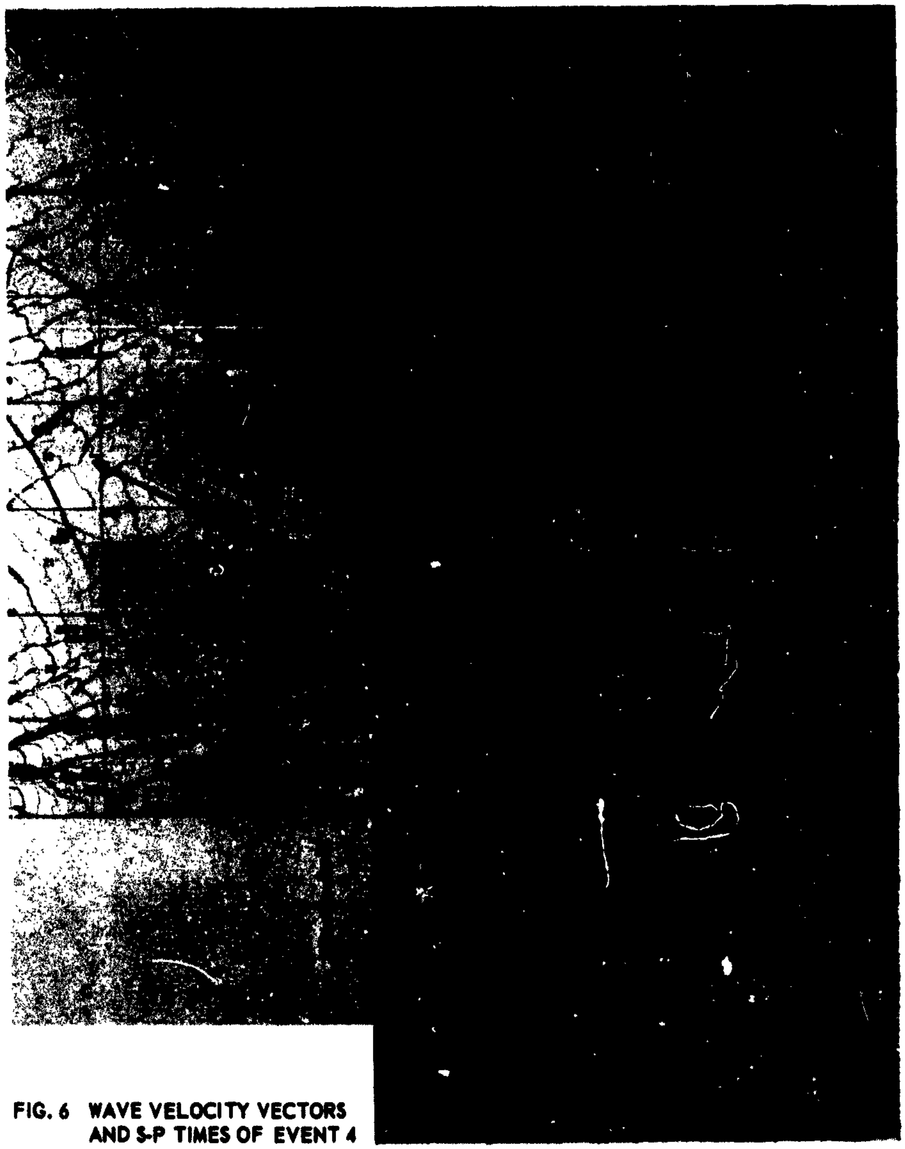

FIG. 6 WAVE VELOCITY VECTORS AND S-P TIMES OF EVENT 4

RA-4322-8

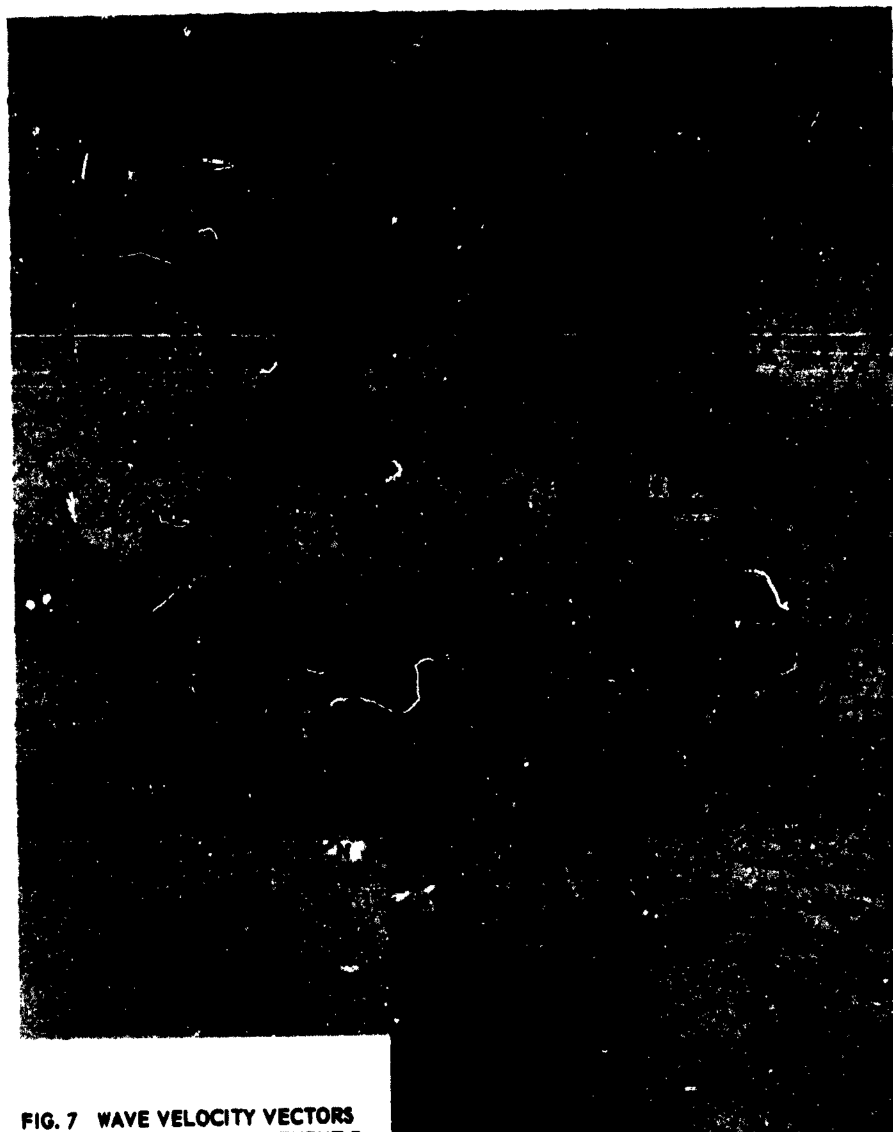

FIG. 7 WAVE VELOCITY VECTORS AND S-P TIMES OF EVENT 7

RA-4328-11

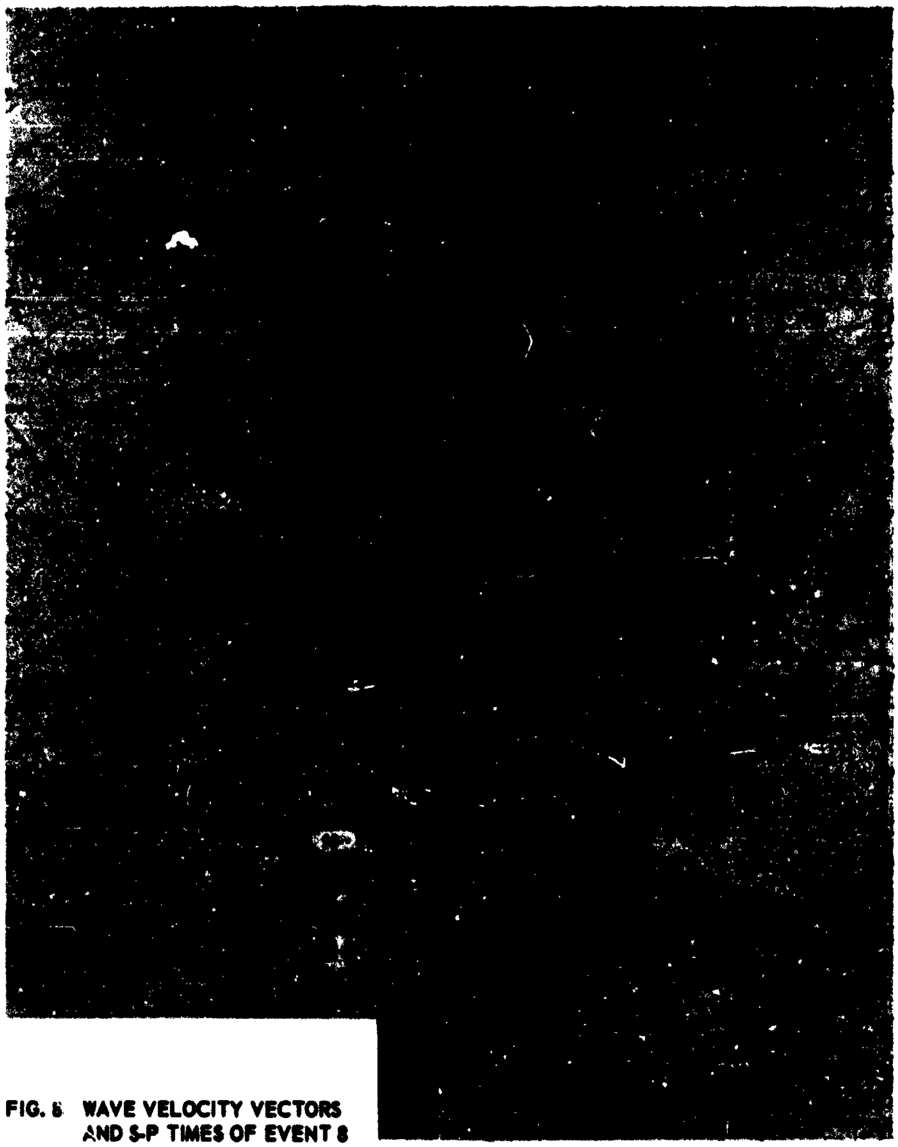

FIG. 5 WAVE VELOCITY VECTORS AND S-P TIMES OF EVENT 8

RA-4363-18

Table II

SLANT DISTANCES TO EVENT FOCI

Event	Station	Slant Distance to Focus (km)
3	A	24
	B	37.5
	C	30
4	A	< 15
	B	< 15
	C	7.5
6	A	216
	B	223
7	A	203
	B	21.5
	C	21.5
8	A	< 15
	B	< 15
	C	< 15
9	A	82
	B	75

Where apparent velocities and vectors were plotted, attempts were made to determine focal depths, with conflicting results, due most likely to the delays and refractions produced by inhomogeneities of the ground. Three examples are discussed below:

Event 3. Velocities of approximately 5.2 km/sec were registered at Stations A and C (Fig. 5). This indicates wave travel at depths below 0.8 km implying a distanct source. Data at C were ambiguous; hence, two possible vectors are shown. The direction of arrival at Station B shows that the wave has been refracted. If its refraction occurred across the fault plane just north of the array, its direction indicates a higher velocity south of the fault; however, the apparent velocity of 3.8 km/sec contradicts this. Using data from Stations A and C (the east vector of C), the waves appear to originate at a horizontal distance of 30 km northeast of Station A, 26 km north-northeast of C, and 31.7 km north-northeast of B. According to S-P times, the slant distance is 24 km from A, 30 km from C, and 37.5 km from B. Assuming a shallow source at the vectorial fix, the arrival time differences yield inconsistent values for the interstation velocities. Accepting the S-P times as the most reliable information, it can be said that the source of Event 3 lies between 20 and 30 km north or northeast of Socorro.

<u>Event 4</u>. The data from Stations A and B indicate that the epicenter of this event was in Section 34, about 6.5 km southwest of Socorro. The high apparent velocity at Station C would be characteristic of such a source, but the divergent velocity vector at Station C vitiates this solution. The S-P interval at Station C corresponds to a slant distance of approximately 7 km.

<u>Event 7</u>. Horizontal refraction at Station B prevented determination of apparent velocity; neither wave direction nor apparent velocity could be determined at Station C. The wave direction, apparent velocity, and S-P time at Station A yield a 20.3 km epicenter distance and 19.2 km focal depth; this places the source under the Socorro range east-northeast of Socorro. On the other hand, the S-P time at Station B gives a slant distance of 21.5 km; this slant distance combined with the epicenter distance dermined from Station A gives a depth of 10.4 km; similarly the S-P time at Station C corresponds to a depth of 9.2 km. Furthermore, the difference in arrival times between Stations A and B gives a trace velocity of 19.5 km/sec, which is unreasonably high, and indicates different time delays occurring along the raypaths.

CONCLUSIONS

No adequate determination of foci could be made in this investigation. Perhaps a larger number of events would have yielded some more readable records, permitting conclusions on the substructure to be drawn and compensated for. The likelihood of low-velocity beds of clay and alluvium underlying the basalt flows, and the presence of extensive faulting and horizontal discontinuities causing refractions and time-delays along the raypaths, make foci determinations very difficult. Data obtained by NMIMT in tunnels in the bedrock are probably much more reliable.

Were the Socorro area to be investigated as a site of a suspicious seismic event that might have derived from a clandestine underground nuclear explosion, it would be difficult to determine whether the observed earthquakes were aftershocks of the event or merely continuous seismic background _if_ this determination depended upon locating the events. The presence of refractions and travel-time delays obscure the exact locations of the sources. The differences in the vector configurations and S-P times for the various events indicate sources at various points in the range and outside of it; some events could be normal seismic activity (as we now have at Socorro), while others could be explosion aftershocks. In on-site inspections a lack of geologic knowlege may result in seismometers being located on complex geologic sites such as were used in this project. During a longer period of recording, enough events might be sampled to provide clues to the refractive properties of the local geologic structure.

REFERENCES

1. Sanford, A. R. and C. R. Holmes, Microearthquakes near Socorro, New Mexico, J. Geophys. Res. 67, 11, 4449-4459 (October 1962)

2. Darton, N. H., Geologic Structure of Parts of New Mexico, U.S. Geological Survey Bull. 726 (II), 173-275 (1922)

3. Lasky, S. G., Ore Deposits of Socorro County, New Mexico, New Mexico School of Mines Bull. No. 8, 139 pp., 1932

4. Miesch, A. T., Geology of the Luis Lopez Manganese District, Socorro County, New Mexico, New Mexico Bureau of Mines and Mineral Resources, Circular 38, 31 pp., 1956

5. Darton, N. H., Geologic Map of New Mexico, U.S. Geological Survey, Washington, D.C., 1928

Appendix

DATA FROM SEISMIC EVENTS

Appendix

DATA FROM SEISMIC EVENTS

Following are the seismic data and results of calculations from these data used to locate and interpret the nine events recorded near Socorro, New Mexico, in December 1961.

EVENT 1 - 25 December 1961

Station Unit	Arrival Time (GCT)	Vector*	Azimuth (deg)	Apparent Velocity (km/sec)	Distance to Epicenter (km)
A	Not recording				
B	Not Recording				
C	16:51:55	---			

*Seismometer numbers from which azimuth was determined

Station Unit	S-P (sec)	Slant Distance (km)	Velocity (km/sec)	Record Quality
A				
B				
C	< 2	< 15		Weak signal, not expanded

Location: Local source.

Depth: Undetermined.

EVENT 2 - 26 December 1961

Station Unit	Arrival Time (GCT)	Vector*	Azimuth (deg)	Apparent Velocity (km/sec)	Distance to Epicenter (km)
A	04:50:40	---			
B	Not visible				
C	04:50:40	---			

*Seismometer numbers from which azimuth was determined

Station Unit	S-P (sec)	Slant Distance (km)	Velocity (km/sec)	Record Quality
A	< 2	< 15		Weak, not expanded
B				No visible trace
C	< 2	< 15		Weak, not expanded

Location: Local source.

Depth: Undetermined.

EVENT 3 - 26 December 1961

Station Unit	Arrival Time (GCT)	Vector*	Azimuth (deg)	Apparent Velocity (km/sec)	Distance to Epicenter (km)
A	07:51:40.569	5-3-1 5-3-2	} 211	5.08 5.36	30 by AC fix
B	07:51:40.732	3-2-6	248	3.8	31.7 by AC fix
C	07:51:39.879	4-5-1	220 200	5.95 5.28	26 by AC fix

*Seismometer numbers from which azimuth was determined.

Station Unit	S-P (sec)	Slant Distance (km)	Velocity (km/sec)	Record Quality
A	3.2	24	5.2	Fair vector agreement, good records
B	5.0	37.5	5.2	Poor record, only three traces
C	4.0	30	5.2	Fair record, but ambiguous

Location: 20 to 30 km north or northeast of Socorro

Depth: Undetermined.

Comments and Conclusions: Assuming an epicenter at the AC fix, arrival times at Stations B and C give an apparent velocity of 6.7 km. Arrival times at Stations A and C give an apparent velocity of 3.8 km/sec. Arrival times at Stations A and B give an apparent velocity of 19.5 km/sec.

EVENT 4 - 26 December 1961

Station Unit	Arrival Time (GCT)	Vector*	Azimuth (deg)	Apparent Velocity (km/sec)	Distance to Epicenter (km)
A	08:32:04.4	3-5-1 4-5-1	281 281	6.7 6.6	
B	08:32:04.30	3-2-6	245-1/2	4.5	
C	08:32:04.?	4-1-6	166	21.2	

*Seismometer numbers from which azimuth was determined.

Station Unit	S-P (sec)	Slant Distance (km)	Velocity (km/sec)	Record Quality
A	< 2	< 15		Good record and agreement
B	< 2	< 15		Fair record, only three traces
C	1.0	7.5	5.2	Fair record

Location: In vicinity of Blue Canyon, Socorro Range.

Depth: Undetermined.

Comments and Conclusions: Vectors A and B meet in Section 34, ~6.5 km SW of Socorro; but because of known refraction at B and the divergent vector at C, this solution can not be accepted. The high apparent velocity at C and short S-P times seem to indicate a focus near Station C.

EVENT 5 - 26 December 1961

Station Unit	Arrival Time (GCT)	Vector*	Azimuth (deg)	Apparent Velocity (km/sec)	Distance to Epicenter (km)
A	Not visible				
B	Not visible				
C	16:50:46	---			

*Seismometer numbers from which azimuth was determined.

Station Unit	S-P (sec)	Slant Distance (km)	Velocity (km/sec)	Record Quality
A				No visible trace
B				No visible trace
C	?			Very weak, not expandable

Location: Undetermined

Depth: Undetermined

EVENT 6 - 26 December 1961

Station Unit	Arrival Time (GCT)	Vector*	Azimuth (deg)	Apparent Velocity (km/sec)	Distance to Epicenter (km)
A	21:00:30	---			
B	21:00:30	---			
C	Not visible				

*Seismometer numbers from which azimuth was determined

Station Unit	S-P (sec)	Slant Distance (km)	Velocity (km/sec)	Record Quality
A	29	216		Weak, not expandable
B	30	223		Weak, not expandable
C				No visible trace

Location: Approximately 200 km from Socorro

Depth: Undetermined.

Comments and Conclusions: Distant earthquake.

EVENT 7 - 27 December 1961

Station Unit	Arrival Time (GCT)	Vector*	Azimuth (deg)	Apparent Velocity (km/sec)	Distance to Epicenter (km)
A	20:13:37.48	4-6-1	250	6.1	Divergent
B	20·13:37.35	2-3	259	?	Divergent
C	20:13:40	---			

*Seismometer numbers from which azimuth was determined.

Station Unit	S-P (sec)	Slant Distance* (km)	Velocity (km/sec)	Record Quality
A	3.15	23.4	5.2	Fair record.
B	2.9	21.5	5.2	Third arrival or another event 34.2 sec after P-wave arrival
C	2.9	21.5	5.2	Record noisy, not expandable.

*The horizontal distance to Station A was calculated to be 20.3 km on a basis of S-P time and apparent velocity.

Location: Approximately 20 km north or northeast of Socorro.

Depth: 19.2 km according to data from Station A. If the epicenter calculated from Station A is accepted, data from Station B give a depth of 10.4 km, and data from Station C give 9.2 km. This makes the Station A data suspect.

EVENT 8 - 27 December 1961

Station Unit	Arrival Time (GCT)	Vector*	Azimuth (deg)	Apparent Velocity (km/sec)	Distance to Epicenter (km)
A	21:03:39.7	---			
B	21:03:38.78	6-2-3	1-1/2	10.2	
C	21:03:~40	---			

*Seismometer numbers from which azimuth was determined.

Station Unit	S-P (sec)	Slant Distance (km)	Velocity (km/sec)	Record Quality
A	< 2	< 15		Weak, not expandable
B	< 2	< 15		Poor record; three channels only
C	< 2	< 15		Very weak, not expandable

Location: Local, in Socorro or Chupadero range.

Depth: Undetermined.

Comments and Conclusions: Vector unreliable.

EVENT 9 - 27 December 1961

Station Unit	Arrival Time (GCT)	Vector*	Azimuth (deg)	Apparent Velocity (km/sec)	Distance to Epicenter (km)
A	21:14:25	---			
B	21:14:18	---			
C	Not visible				

*Seismometer numbers from which azimuth was determined.

Station Unit	S-P (sec)	Slant Distance (km)	Velocity (km/sec)	Record Quality
A	11	82		Weak, not expandable
B	10	75		Weak, not expandable
C				No visible trace

Location: Approximately 75 km from Socorro.

Depth: Undetermined.

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